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SELF VS. OTHER: NEURAL CORRELATES UNDERLYING AGENT IDENTIFICATION BASED ON UNIMODAL AUDITORY INFORMATION AS REVEALED BY ELECTROTOMOGRAPHY (SLORETA)

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Abstract—Recent neuroscientific studies have identified activity changes in an extensive cerebral network consisting of medial prefrontal cortex, precuneus, temporo–parietal junction, and temporal pole during the perception and identification of self- and other-generated stimuli. Because this network is supposed to be engaged in tasks which require agent identification, it has been labeled the evaluation network (e-network). The present study used self- versus other-generated movement sounds (long jumps) and electroencephalography (EEG) in order to unravel the neural dynamics of agent identification for complex auditory information. Participants ($N = 14$) performed an auditory self–other identification task with EEG. Data was then subjected to a subsequent standardized low-resolution brain electromagnetic tomography (sLORETA) analysis (source localization analysis). Differences between conditions were assessed using *t*-statistics (corrected for multiple testing) on the normalized and log-transformed current density values of the sLORETA images. Three-dimensional sLORETA source localization analysis revealed cortical activations in brain regions mostly associated with the e-network, especially in the medial prefrontal cortex (bilaterally in the alpha-1-band and right-lateralized in the gamma-band) and the temporo–parietal junction (right hemisphere in the alpha-1-band). Taken together, the findings are partly consistent with previous functional neuroimaging studies investigating unimodal visual or multimodal agent identification tasks (cf. e-network) and extent them to the auditory domain. Cortical activations in brain regions of the e-network seem to have functional relevance, especially the significantly higher cortical activation in the right medial prefrontal cortex.

Key words: EEG source localization, frequency analysis, agent identification, e-network, audition, complex movement sound.

INTRODUCTION

Every day, a huge number of different sounds from environmental sources are picked up by the ears. The human brain processes this information, giving rise not only to the phenomenon of auditory perception, but also to the identification of an infinite number of different environmental sounds. To successfully interact with the environment, humans need to identify whether a perceived stimulus is self-generated or generated by another agent (hereafter, other-generated), which is also known as agent identification (Buckner and Carroll, 2006). In recent years, neuropsychologists have been highly interested in understanding how agent identification leads to the mental attribution of features of the experienced self, also known in the literature as self-processing (Christoff et al., 2011). A large number of neuroimaging studies have explored the neural correlates underlying self-processing with an emphasis on self–other identification paradigms, mostly using unisensory visual stimuli or multisensory visual and auditory stimuli (for an overview, see Legrand and Ruby, 2009). The results of many of these studies have revealed activations in a fronto–parietal network lateralized to the right hemisphere of the human brain. Legrand and Ruby (2009) showed in their meta-analysis that self-processing involves a refined cerebral network, which the authors called the evaluation network or e-network, that consists of the medial prefrontal cortex [MPFC; Brodmann areas (BAs) 9 and 32], the precuneus (BA 7), the temporo–parietal junction (TPJ; BAs 39 and 40), and the temporal pole (BA 38). However, neurophysiological evidence that these results

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Abbreviations: A1, primary auditory cortex; A2, secondary auditory cortex ; Ag/AgCl, silver/silver chloride; BA, Brodmann area; BOLD, blood-oxygenation-level-dependent; dB, decibel; dB/oct, decibel per octave; EEG, electroencephalography; EOG, electro-oculography; ERP, event-related potential; fMRI, functional magnetic resonance imaging; Hz, hertz; IFG, inferior frontal gyrus; kΩ, kiloOhm; MNI, Montreal Neurological Institute; PCG, precentral gyrus; PET, positron-emission tomography; rMPFC, (right) medial prefrontal cortex; (r)PHG, (right) parahippocampal gyrus; (r)TMS, (repetitive) transcranial magnetic stimulation; (r)TPJ, (right) temporo–parietal junction; rTMS, repetitive transcranial magnetic stimulation; RTs, reaction times; SDT, signal detection theory; sLORETA, standardized low-resolution brain electromagnetic tomography; STG, superior temporal gyrus; V1, primary visual cortex; µV, microvolt.

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apply to self–other identification tasks that are based on purely unimodal auditory stimulation is still lacking.

To date, only a few, mostly behavioral studies have employed self-other identification paradigms to investigate unimodal auditory agent identification, for example, agent identification of self- versus other-generated hand-clapping sounds (Knoblich and Repp, 2009) and self- versus other-generated piano playing in synchrony with music (Repp and Knoblich, 2004). In the context of auditory agent-identification tasks, the rhythm and periodicity of a movement sound builds a fundamental dynamic and temporal concept that is best represented through its characteristic sound features (MacPherson et al., 2009). As a result, each person's movement (e.g., running or long jumping) should generate a unique and identifiable sound pattern.

In the research field of human movement science, it has been assumed that auditory information is a relevant source of information not only during movement execution, but also during movement perception (Agostini et al., 2004). Additionally, auditory information can be seen as a factor guiding motor action in sports and athletes should benefit from successfully distinguishing between their own and others movement sounds based on the auditory information available (Agostini et al., 2004). In this line of research, a recent behavioral study investigated the role of temporal auditory cues in an unimodal auditory agent identification task (Murgia et al., 2012). Golfers were asked to identify the corresponding agent of previously recorded self- and other-generated golf-swing sounds. Behavioral results demonstrated that (1) the golfers were capable of successfully distinguishing self- from other-generated golf-swing sounds on the basis of available auditory information and (2) certain aspects of auditory information (e.g., temporal cues) seem to play an important role in identifying oneself as the agent causing a particular golf-swing sound.

To our knowledge, the present neurophysiological study is the first to use previously recorded auditory stimuli, in this case complex movement sounds, to study the underlying neural correlates of self–other identification based on unimodal auditory information. We took an ecological approach and used previously recorded natural long-jump sounds. The question remains how the human brain distinguishes self-generated from other-generated unimodal auditory information. Furthermore, whether identification of self-generated versus other-generated unimodal auditory information relies on the same neural structures and networks as identification with unimodal visual or multimodal stimulation (cf. e-network) should be investigated. Both questions can be studied with functional neuroimaging techniques such as PET (positron emission tomography) and fMRI (functional magnetic resonance imaging). In addition to using these common neurophysiological techniques, researchers have made various attempts to model and localize brain electrical activity based on recorded electroencephalography (EEG) data in situations where fMRI and PET are not available. Standardized low-resolution brain electromagnetic tomography (sLORETA) is an electrocortical tomography technique for analyzing such EEG data (Pascual-Marqui, 2002). Application of sLORETA to EEG data can be used to determine the intracerebral localization and strength of brain electrical activity, which is best described in an inhibiting and facilitating manner. The sLORETA method estimates the maximally smoothed linear inverse solution using a mathematical algorithm to make assumptions about the location of neural generators of underlying electrical brain activity, based on the method of Pascual-Marqui et al. (2002). Furthermore, sLORETA brain electrical functional imaging analysis is able to localize brain electrical activity regardless of the number of neural generators by solving the inverse problem based on the physiologically well-established theory that neighboring neural populations are synchronously active and will thus have the same charging state (Silva et al., 1991). Therefore, the minimum-norm method was expanded with the so-called smoothness-assumption (Llinas, 1988; Gray et al., 1989). Following these two assumptions, sLORETA chooses the most plausible computation from all possible computations that closely match the theory of the synchronous activity of neighboring neural populations (Silva et al., 1991). A recent EEG–sLORETA study by Walla et al. (2008) (localization of neural correlates of self-awareness) and an EEG study combined with sLORETA functional tomography mapping analysis in conjunction with fMRI confirmed that sLORETA is able to accurately localize underlying neural generators of brain electrical activity (Mulert et al., 2004). In the latter study, researchers employed an auditory oddball task to compare brain activations measured with fMRI with those obtained with a subsequent sLORETA source-localization analysis. Results indicate that sLORETA is able to successfully identify the source of neural generators (1) in the auditory domain and (2) with minimal localization error (which is due to the blurriness of the obtained sLORETA images).

Therefore, analysis of EEG data in combination with sLORETA can be seen as a useful tool for studying the physiology of the human brain because the method combines traditional EEG recordings with three-dimensional source localization of electrical brain activity. However, to date EEG activity and oscillations in cortical regions associated with the aforementioned e-network have not been investigated. In summary, the objective of this study was to localize the underlying neural correlates of agent identification based on unimodal auditory stimulation using EEG in combination with a subsequent sLORETA source localization analysis.

Taking into account the findings obtained by prior behavioral and neuroimaging studies, we hypothesized that participants would successfully identify previously recorded self- and other-generated unimodal auditory information (long-jump sounds), respectively. Furthermore, we hypothesized that sLORETA would localize electrocortical activity in brain regions associated with agent identification and self-processing (cf. e-network). Thus, the identification of self- versus